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NOTE

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Fat suppression for ultrashort echo time imaging using a novel soft-hard composite radiofrequency pulse

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Purpose: To design a soft-hard composite pulse for fat suppression and water excitation in ultrashort echo time (UTE) imaging with minimal short T_2 signal attenuation.

Methods: The composite pulse contains a narrow bandwidth soft pulse centered on the fat peak with a small negative flip angle (–α) and a short rectangular pulse with a small positive flip angle (α). The fat magnetization experiences both tipping-down and -back with an identical flip angle and thus returns to the equilibrium state, leaving only the excited water magnetization. Bloch simulations, as well as knee, tibia, and ankle UTE imaging studies, were performed to investigate the effectiveness of fat suppression and corresponding water signal attenuation. A conventional fat saturation (FatSat) module was used for comparison. Signal suppression ratio (SSR), defined as the ratio of signal difference between non-fat-suppression and fat-suppression images over the non-fat-suppression signal, was introduced to evaluate the efficiency of the composite pulse.

Results: Numerical simulations demonstrate that the soft-hard pulse has little saturation effect on short T_2 water signals. Knee, tibia, and ankle UTE imaging results suggest that comparable fat suppression can be achieved with the soft-hard pulse and the FatSat module. However, much less water saturation is induced by the soft-hard pulse, especially for short T_2 tissues, with SSRs reduced from 71.8 ± 6.9% to 5.8 ± 4.4% for meniscus, from 68.7 ± 5.5% to 7.7 ± 7.6% for bone, and from 62.9 ± 12.0% to 4.8 ± 3.2% for the Achilles tendon.

Conclusion: The soft-hard composite pulse can suppress fat signals in UTE imaging with little signal attenuation on short T_2 tissues.

KEYWORDS
fat suppression, soft-hard composite pulse, ultrashort echo time

1 | INTRODUCTION

Ultrashort echo time (UTE) sequences with echo times <100 μs can detect fast decaying signals and provide a much higher signal to noise ratio for short T_2 tissues than conventional clinical gradient recalled echo–type sequences with much longer echo times.[1] In the past decade, these UTE sequences have been widely investigated for both morphological and quantitative imaging of short T_2 tissues, including calcified cartilage, menisci, tendons, ligaments, bone, and myelin.[2-7]

Fat suppression is very important for UTE imaging of musculoskeletal tissues.[8-10] This is because UTE imaging

tends to show a high fat signal, attributed to fat's high proton density and short T_1 value, which lead to low contrast for short T_2 tissues. Additionally, UTE imaging of short T_2 tissues often suffers from fat contamination attributed to partial volume effect, as well as from off-resonance artifacts induced by non-Cartesian UTE acquisition. Thus, for both high contrast morphological imaging and accurate quantitative imaging of short T_2 tissues, it is crucial to incorporate fat-suppression techniques with UTE imaging.

The most commonly used approach for fat suppression in clinical practice is the chemical shift-based fat saturation (also called FatSat module), which includes a spectrally selective radiofrequency (RF) pulse followed by a gradient spoiler. However, the FatSat module is not well suited for short T_2 imaging because of its strong direct attenuation of the broad frequency spectrum of short T_2 tissues.[11] Furthermore, a relatively large saturation flip angle (i.e., no less than 90°) is used in the FatSat module, which also leads to indirect signal attenuation induced by the magnetization transfer (MT) effects, especially for the collagen-rich tissues.[12] Other techniques, such as the long T_2 suppression RF pulse[13,14] or the inversion recovery preparations,[15-18] can generate high contrast in morphological UTE imaging of short T_2 tissues. However, they can only be conditionally useful for quantitative UTE imaging because the long T_1 components in short T_2 tissues are also partially suppressed by these techniques.[19,20] Moreover, fat-separation–based methods, such as the single-point Dixon, iterative decomposition of water and fat with echo asymmetry and least-squares estimation and UTE spectroscopic imaging, can be incorporated in both morphological and quantitative UTE imaging.[21-23] However, they require longer acquisition time and data postprocessing.

In this study, we proposed a new fat-suppression RF pulse for UTE imaging of short T_2 tissues with well-preserved short T_2 signals using a soft-hard composite pulse. Bloch simulations were performed to investigate its signal attenuation effects on both short and long T_2 tissues, which were then compared with both nonfat suppression excitation and the conventional FatSat technique. Then, in vivo knee and tibia as well as ex vivo ankle UTE imaging studies were performed to evaluate the effectiveness of fat suppression and investigate the corresponding short T_2 signal attenuation for both the proposed soft-hard composite pulse and the conventional FatSat module.

2 | METHODS

2.1 | Soft-hard composite pulse design

Features of the newly designed soft-hard composite pulse and the conventional FatSat module are both shown in Figure 1. The proposed fat-suppression pulse or water-excitation pulse consists of 2 RF pulses: 1 soft pulse (minimum-phase Shinnar–Le Roux [mip-SLR] design with a duration of 4.4 ms and spectral bandwidth of 500 Hz) and 1 hard pulse (Figure 1A).[24] The soft pulse centers on the fat peak with a narrow bandwidth. It is used to flip only the fat magnetization and is followed by a short hard pulse with the same flip angle as the soft pulse, which flips both water and fat magnetizations in the opposite direction. Given that the fat magnetization experiences both tipping down and tipping back with this identical flip angle, most of the fat magnetization returns to the equilibrium state. Subsequently, most of the fat signals are not received by the subsequent UTE acquisitions. In addition, the soft pulse has been designed with a narrow bandwidth and with a pulse duration of several milliseconds; thus, the RF power of the soft pulse is relatively low. The soft pulse excitation is therefore expected to have little saturation effect on the water magnetizations. This makes it possible for the water signals to be effectively excited by the following hard pulse.

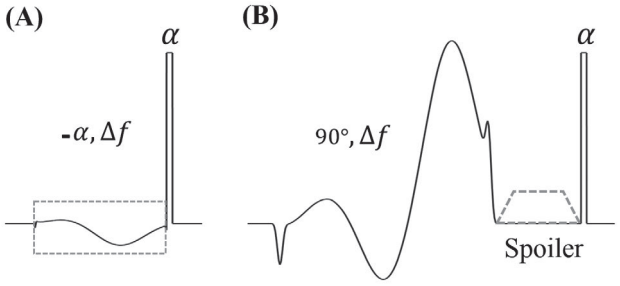

FIGURE 1 The proposed soft-hard composite pulse (A) and the conventional FatSat module (B). A soft RF pulse centered on fat on-resonance frequency (Δf) with a negative flip angle (–α) was used to flip the fat magnetization only, followed by a short hard pulse with a positive flip angle (α) to flip all the magnetizations in the opposite direction (A). The commonly used FatSat module is shown in (B) for comparison. A 90° soft pulse centered on fat on-resonance frequency was used to flip down the fat magnetization, and then all the excited transverse magnetizations were crushed by a gradient spoiler. A following hard pulse was used for water signal excitation. The RF phases of soft pulses in (A) and (B) were determined by their center frequencies

The conventional FatSat technique consists of a saturation pulse (mip-SLR design with a duration of 8 ms and bandwidth of 500 Hz) centered on the fat peak with a flip angle no less than 90°, followed by a gradient spoiler to crush all the excited transverse magnetizations (Figure 1B). Then, a short hard pulse is utilized for signal excitation.

Typically, the flip angle of the soft pulse (the same as the excitation flip angle) in the soft-hard composite pulse is much lower than 90° for UTE imaging. Therefore, both direct and indirect saturations (i.e., MT effect) of the water signals produced by the soft pulse in the proposed soft-hard composite pulse are much less than the water-signal attenuations induced by the FatSat module.

2.2 | Numerical simulations

Bloch simulation was carried out to compare the excitations of a single hard pulse, the proposed soft-hard composite pulse, and the conventional FatSat module for both short and long T_2 imaging with tissue T_2s of 0.3, 0.5, 1, 2, 5, and 20 ms. The T_2 of fat was 20 ms. The excitation flip angle was set to 10° for all 3 RF pulses in simulation; the other parameters were as follows: (1) the single hard pulse: duration was 50 μs; (2) the soft-hard composite pulse: mip-SLR design, 4.4 ms, bandwidth of 500 Hz, and center frequency of –440 Hz (i.e., off-resonance frequency of fat at 3T); hard pulse duration was 50 μs; (3) the GE product FatSat module: mip-SLR design, 8 ms, bandwidth of 500 Hz, center frequency of –440 Hz, and flip angle of 90°; the spoiler gradient area was large enough to keep the dephasing in a single voxel no less than 4π; the duration of hard pulse excitation was 50 μs.

Numerical simulations for UTE acquisitions were also performed to compare the signal intensities using excitations of the single hard pulse, the proposed soft-hard composite pulse, and the FatSat module. Identical pulse shapes, as above, were utilized in this simulation; other sequence parameters were as follows: TR = 50 ms, nominal TE = 20 μs, and excitation flip angles ranged from 0° to 50°. A constant T_1 value of 800 ms and variable T_2 values of 0.3, 0.5, 1, 2, 5, and 20 ms were used for simulation. The nominal TE is defined as the time between the end of the hard pulse and the k-space center.

2.3 | UTE imaging

To compare UTE imaging with and without fat suppression, in vivo knee and tibia imaging, as well as ex vivo ankle imaging, was performed on a 3T whole-body scanner (GE Healthcare Technologies, Milwaukee, WI). An 8-channel transmit/receive knee coil was used for both RF transmission and signal reception. A 3D UTE-Cones sequence was used for both short and long T_2 tissue imaging with unique k-space trajectories that sampled data along evenly spaced twisting paths in the shape of multiple cones.[17,18] Data sampling started at the center of k-space as soon as possible after the RF excitation with a minimal nominal TE of 32 μs.

Fat suppression was carried out using both the proposed soft-hard composite pulse and the GE product FatSat module. The single hard pulse excitation UTE imaging without fat suppression was also utilized for comparison. All the RF pulse shapes are identical to the pulses used in the simulation section. The following UTE imaging sequences were repeated using the above 3 excitation pulses, respectively. Five healthy volunteers (22–35 years old) were recruited for knee joint imaging; the sequence parameters of 3D UTE-Cones were as follows: field of view (FOV) = 15 × 15 × 9.6 cm^3, acquisition matrix = 256 × 256 × 32, TE = 32 μs, flip angle = 5°, TR = 20 ms, and scan time = 3 minutes 36 seconds. Six healthy volunteers (22–35 years old) were recruited for tibia imaging; the sequence parameters of 3D UTE-Cones were as follows: FOV = 12 × 12 × 16 cm^3, matrix = 192 × 192 × 32, TE = 32 μs, flip angle = 5°, TR = 20 ms, and scan time = 2 minutes 45 seconds. Five healthy volunteers (28–84 years old) were recruited for ankle imaging; the parameters of UTE-Cones imaging were as follows: FOV = 11 × 11 × 6 cm^3, matrix = 256 × 256 × 30, TE = 32 μs, flip angle = 5°, TR = 20 ms, and scan time = 3 minutes 22 seconds. Informed consent was obtained from all subjects in accord with the guidelines of the institutional review board.

2.4 | Data analysis

To evaluate both the fat suppression and the water attenuation for the proposed soft-hard composite pulse and the conventional FatSat module, a signal suppression ratio (SSR; unit in percentage), defined as the fraction of the subtracted image between non-fat-suppression image and fat-suppression image by the non-fat-suppression image, was used. A higher SSR value corresponded to better fat suppression or a stronger water attenuation induced by the fat-suppression technique used. Both the pixel-wised SSR maps and region of interest (ROI)-based signal mean and standard deviation values within all tissues were used for comparison. All analysis algorithms were written in Matlab 2017b (The MathWorks Inc., Natick, MA).

3 | RESULTS

Numerical simulation results of the excitation profiles or spectrums for the single hard pulse, proposed soft-hard composite pulse, and conventional FatSat module are shown in Figure 2. As can be seen from the transverse magnetization (i.e., M_{xy}) profiles in Figure 2A-F, both the soft-hard and the FatSat pulses were able to null the fat signals at –440 Hz. However, the signal-nulling bandwidth of the soft-hard pulse was narrower than the FatSat pulse, and 2 side lobes appeared in both sides of the fat peak. This was induced by the off-resonance excitation during the soft pulse, when the spin had a different on-resonance frequency than the fat center frequency. However, when tissue T_2 was getting shorter, the profiles approached those of the standard single hard pulses. On the other hand, though there were larger side lobes in the excitation of fatty tissues, they had little effect on the water peak, because of the narrower water spectrum. Consequently, the proposed soft-hard composite pulse had very little effect on both short and long T_2 water signals and therefore generated similar water excitations as the single hard pulse. The FatSat module had a better fat suppression than the soft-hard composite pulse, especially

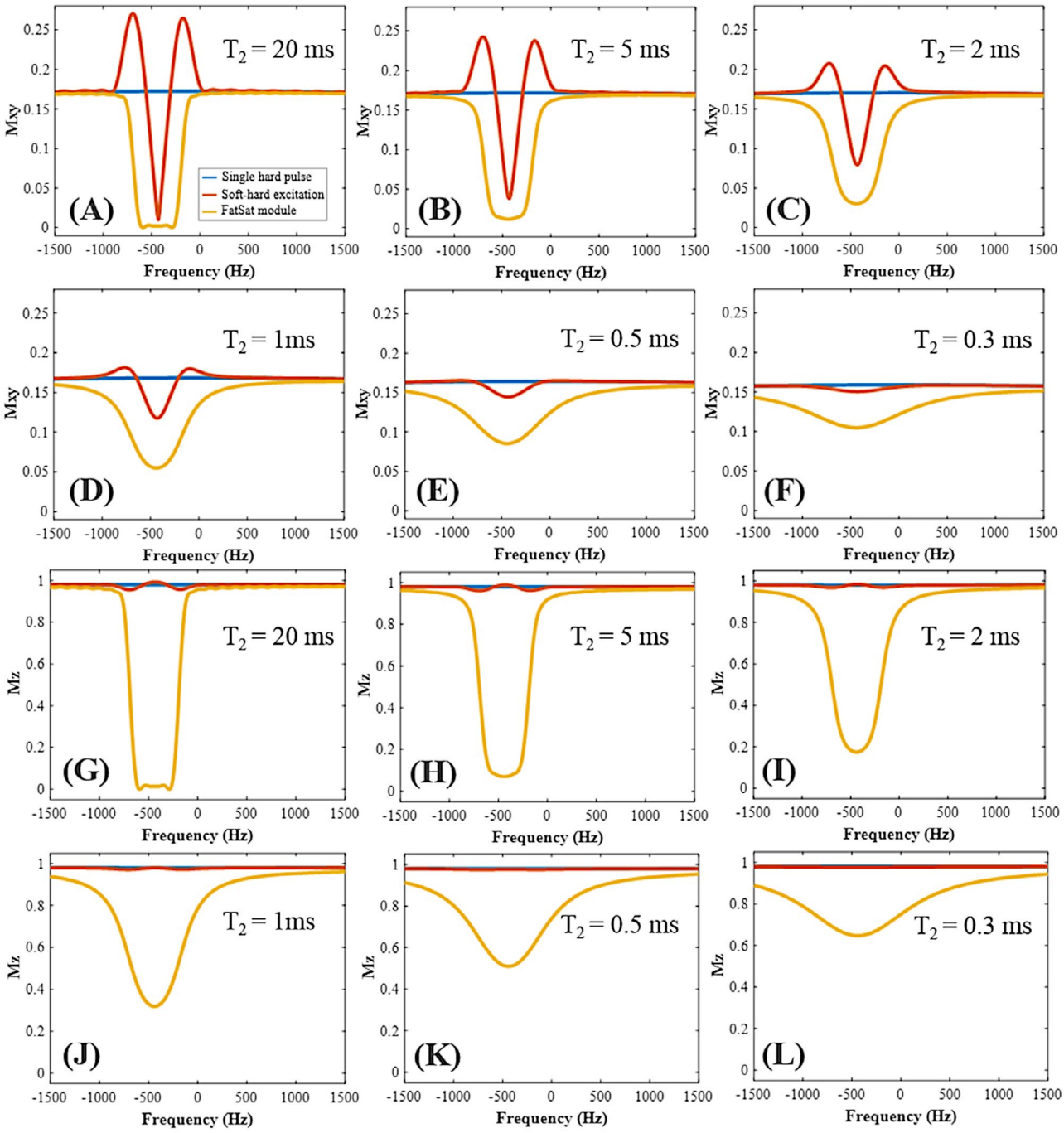

FIGURE 2 Bloch simulations for the excitations of a single hard pulse (blue curves), the proposed soft-hard composite pulse (red curves), and the conventional FatSat module (yellow curves). Both transverse (A-F) and longitudinal (G-L) magnetization profiles were calculated for tissues with different T_2s of 20, 5, 2, 1, 0.5, and 0.3 ms. Much lower saturation effect was observed for the proposed soft-hard composite pulse compared with that of the FatSat module

for the tissue with a broad fat spectrum. In comparison, the high flip angle saturation pulse used in the FatSat module led to a strong direct saturation on the broad spectrum short T_2 water signals. Thus, fewer short T_2 signals were excited compared with those generated by the single hard pulse or the soft-hard pulse.

As can be seen from Figure 2G-L, the longitudinal magnetization (i.e., M_z) profiles generated by the soft-hard pulse is very close to the single hard pulse, which confirms that the soft pulse has little effect on water signals. In contrast, the reduced M_z profiles of the FatSat module, compared with those in both excitations of the single hard pulse and the soft-hard pulse, demonstrate the strong direct attenuations of the short T_2 signals by the FatSat module.

Simulated UTE imaging results are shown in Figure 3. As evidenced by the Mxy signal curves, higher flip angles

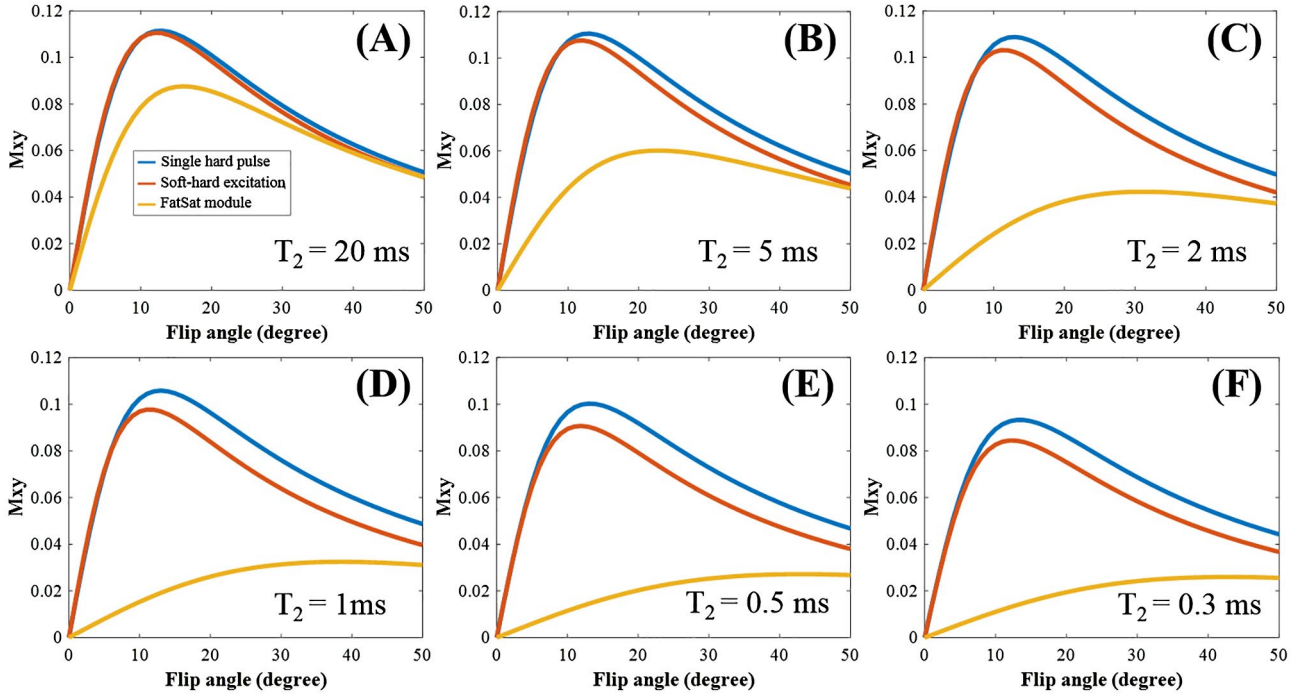

FIGURE 3 Simulations of UTE imaging using the excitations with a single hard pulse (blue curves), the proposed soft-hard composite pulse (red curves), and the conventional FatSat module (yellow curves), respectively. The UTE signal intensities changed with the flip angles ranged from 0° to 50°. Six different T_2s of 20, 5, 2, 1, 0.5, and 0.3 ms were used to simulate both long and short T_2 tissues. All the tissue T_1s were set to a constant value of 800 ms for simulation

demonstrate less-effective excitations compared with the single hard pulse excitation. Stronger signal attenuation is induced by the soft pulse with a higher flip angle. When the excitation flip angles are <10°, the proposed soft-hard pulse can get similar signal intensities as the single hard pulse for both short and long T_2 tissues. In comparison, the derived signal curves of the FatSat module are much lower than those of the single hard pulse and soft-hard pulse because of the large direct saturations.

Figure 4 shows the in vivo knee UTE-Cones imaging results from a 24-year-old volunteer. The first 3 rows are the grayscale images acquired with the single hard pulse, the proposed soft-hard water excitation pulse, and the conventional FatSat module, respectively. The last 2 rows show the SSR colormaps for the 2 fat suppression methods, respectively. The UTE-Cones images with the excitations of the proposed soft-hard pulse and the product FatSat module both demonstrate good fat suppression and much better image contrast than the non-fat-suppression images. The UTE-Cones images with the excitations of a single hard pulse and the soft-hard pulse are displayed with the same value range (i.e., [0, 500]) because of their similar signal intensity levels. In contrast, the FatSat UTE-Cones images are displayed with a much narrower value range (i.e., [0, 200]) because of their lower maximum signal intensities, which were induced by the strong water attenuations (including both direct saturation and MT effect) of the FatSat module. The short T_2 tissues, such as menisci, patellar tendon, and posterior cruciate ligament (PCL; indicated by arrows), in the UTE-Cones images with the soft-hard pulse excitation show much better preserved signal intensities than those in the FatSat UTE-Cones images. The SSR maps also suggest that there were nearly no signal attenuations for either short or long T_2 tissues when using the proposed soft-hard pulse for excitation. In comparison, there were strong attenuations for the water signals in the FatSat UTE-Cones images, especially for the short T_2 tissues. Similar to the simulation results, the fat-suppression technique using the soft-hard pulse was less effective and more spatially inhomogeneous than the FatSat module. This is attributed to the narrow nulling bandwidth and the additional side lobes of the soft-hard pulse, which induce increased sensitivity to the B_0 inhomogeneity.

Figure 5 shows in vivo tibial UTE-Cones imaging results from a 35-year-old volunteer. Like the above knee imaging, the UTE-Cones images with the proposed soft-hard composite pulse excitation show excellent image contrast and well-preserved cortical bone and muscle signals. In comparison, most of the short T_2 signals (i.e., cortical bone and coil elements) are lost in the FatSat UTE-Cones images because of the strong saturation effect of the FatSat module. Ex vivo ankle UTE-Cones imaging results from 3 donors are also shown in Supporting Information Figure S1. Much better SNR and higher contrast of short T_2 tendon signals can be seen in the UTE-Cones images with the soft-hard excitation in comparison to the FatSat UTE-Cones images.

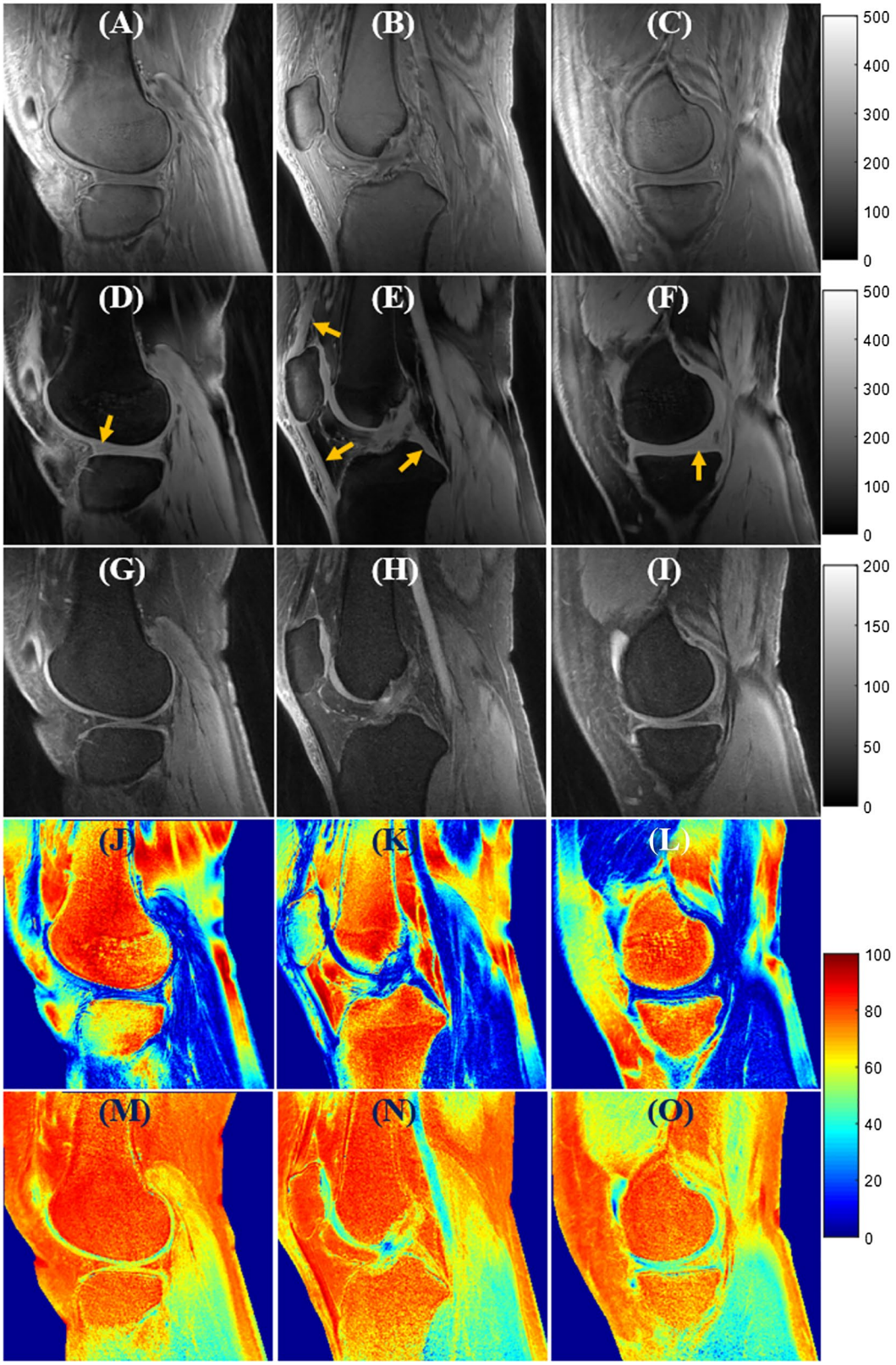

FIGURE 4 In vivo knee joint UTE-Cones imaging (from a 24-year-old volunteer) using excitations with a single hard pulse (A-C), the proposed soft-hard water excitation pulse (D-F), and the conventional FatSat module (G-I). Fat was well suppressed by both the proposed soft-hard pulse and the FatSat module. The short T_2 signals (indicated by yellow arrows in D-F) were much better preserved in the soft-hard excitation images (D-F) compared with FatSat images (G-I). The SSR color maps (soft-hard pulse: J-L; FatSat module: M-O) also suggest that there were almost no signal attenuations for either short or long T_2 tissues when using the proposed soft-hard pulse for excitation. In comparison, there were strong signal attenuations for the water signals in the FatSat UTE-Cones images, especially for the short T_2 tissues

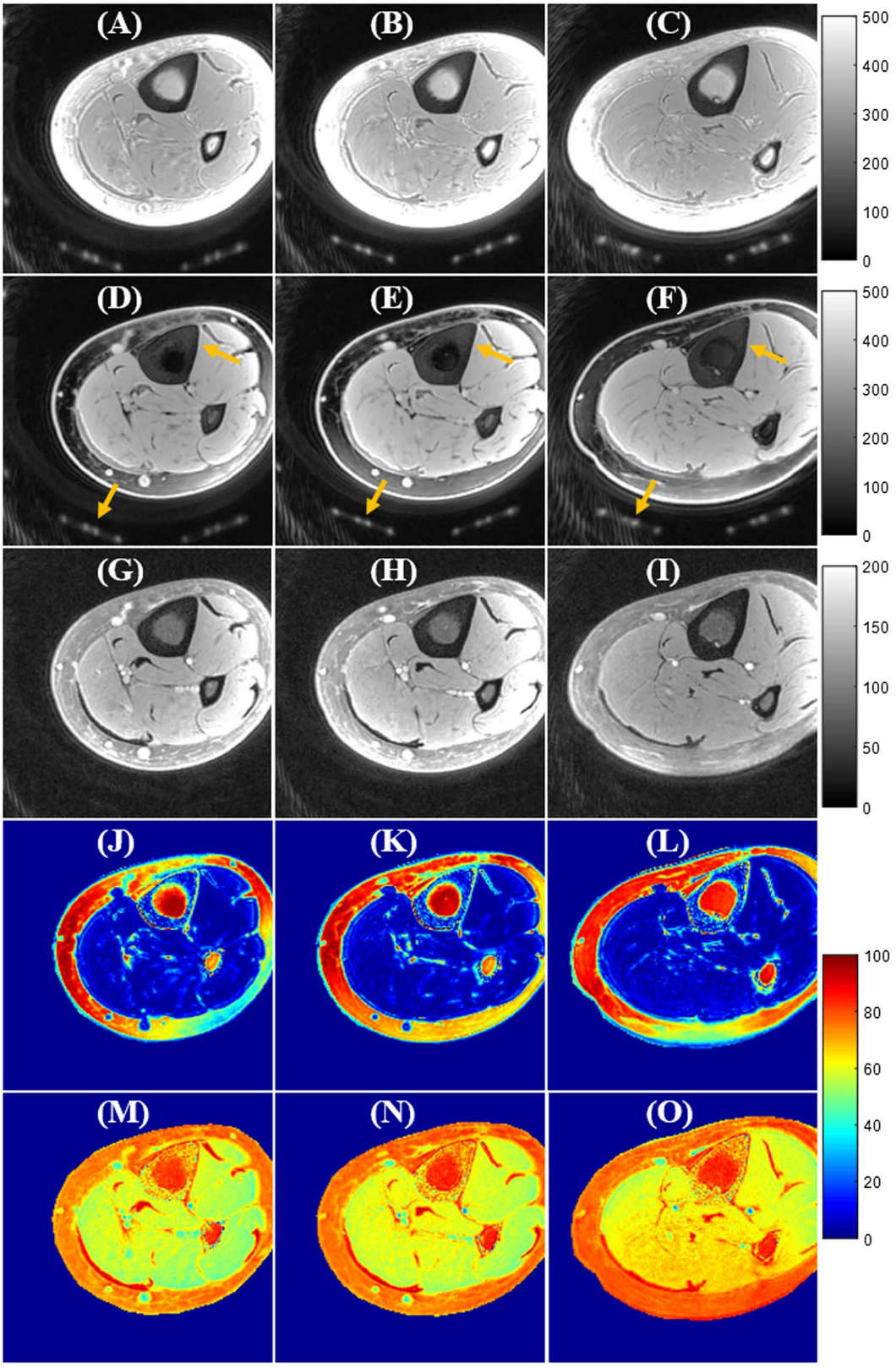

FIGURE 5 In vivo tibia UTE-Cones imaging (from a 35-year-old volunteer) using excitations with a single hard pulse (A-C), the proposed soft-hard water excitation pulse (D-F), and the conventional FatSat module (G-I). Fat was well suppressed by both the proposed soft-hard pulse and the FatSat module. The cortical bone and coil elements (indicated by yellow arrows in D-F) were much better preserved in the soft-hard excitation images (D-F) compared with FatSat images (G-I). The SSR color maps (soft-hard pulse: J-L; FatSat module: M-O) also suggest that there were almost no signal attenuations for either short or long T_2 tissues when using the proposed soft-hard pulse for excitation. In comparison, there were strong signal attenuations for the water signals in the FatSat UTE-Cones images, especially for the short T_2 tissues

Supporting Information Table S1 summarizes the SSR values for all tissues studied in this work. Both short and long T_2 tissues show much decreased SSRs for the proposed soft-hard pulse compared with those of the FatSat module, demonstrating the proposed excitation pulse's higher excitation efficiency. A slightly lower SSR value was observed for marrow fat with the proposed soft-hard pulse. This is because of the narrower signal-nulling bandwidth of the proposed pulse compared with the conventional FatSat module. The results also show relatively high SSR values for the patellar tendon and anterior cruciate ligament (ACL) with the soft-hard pulse, which may be caused by partial volume and fat contamination in the ROIs of patellar tendon and ACL.

4 | DISCUSSION

We have demonstrated in this study that the proposed soft-hard composite pulse is potentially useful for fat suppression in UTE imaging of short T_2 tissues. Numerical simulations show that the proposed soft-hard composite pulse has much lower signal attenuation on water imaging than the conventional FatSat module. In vivo knee and tibia as well as ex vivo ankle UTE imaging demonstrated well-performed fat suppression for the soft-hard pulse excitation. Besides, both the short and long T_2 tissue signals were much better preserved with the soft-hard composite pulse excitation than with the FatSat module for fat suppression. Significantly higher SSRs were achieved with the composite pulse, especially for short T_2 tissues. Such efficient fat-signal suppression may improve MRI-based bone assessments[25-27] and reduce the need for extensive scans for sophisticated multicomponent signal analysis.[28]

The proposed soft-hard composite pulse can preserve the short T_2 signals while suppressing the fat components, thus providing much higher contrast for short T_2 tissues than the non-fat-suppressed images. The soft-hard pulse is relatively sensitive to the B_0 field inhomogeneity because of the narrow bandwidth of the soft pulse. There are also substantial side lobes in the soft-hard pulse excitation that may cause the fat signal to increase in some situations (e.g., in the case where the side lobe locates at the fat peak because of the B_0 inhomogeneity). We can find slightly increased fat signals in some regions with strong B_0 inhomogeneities (e.g., the air-tissue boundary in the middle right of Figure 4D). This phenomenon may occur when the B_0 shift is larger than half of the fat frequency offset (i.e., 1.7 ppm). In our experience with knee imaging, the B_0 inhomogeneity tends to be <0.5 ppm at 3T. To maintain high performance in fat suppression with the soft-hard composite pulse excitation, it is critical to have a system with a relatively uniform B_0 field and/or a high-performing shimming module (e.g., high-order shimming). Though fat suppression using the soft-hard pulse excitation is less uniform than the conventional FatSat module in this study, the image contrast between water and fat tissues with the soft-hard pulse excitation is still better than the FatSat images according to the calculated SSR values. The soft and hard pulses are 2 independent pulses in our soft-hard composite pulse implementation; thus, the center frequency of the soft pulse can be adjusted to account for B_0 inhomogeneity, if necessary. The proposed soft-hard pulse may be less sensitive to the B_1 inhomogeneity for fat suppression given that the fat components always experience the same flip angles in opposite directions. The minimum phase pulse design can shorten the echo time, thus decreasing the T_2 decay during the soft pulse excitation. Then, the fat magnetization tipped down by the soft pulse can be largely tipped back by the hard pulse, thus allowing more efficient fat suppression.

Two groups have reported that the conventional binomial water excitation pulse provides excellent fat suppression with moderate short T_2 signal attenuations in UTE knee imaging.[29,30] Similar simulations were performed in Springer's study (i.e., Figure 4A) as in our study (i.e., Figure 3).[29] Their simulation results demonstrated a stronger water attenuation with the binomial water excitation pulse when the tissue T_2s were getting shorter. However, our simulation results of the proposed soft-hard pulse excitation show a better performance in short T_2 tissue imaging, especially when the excitation flip angles are <10°. Our future studies are expected to compare the above 3 fat suppression techniques for quantitative UTE imaging, such as quantitative measures of T_1,[31,32] $T_{1\rho}$,[33,34] bicomponent T_2^* analysis,[35,36] MT ratio,[37] as well as MT modeling,[38] which will provide more comprehensive understanding about the effect of different fat-suppression schemes.

This study has several limitations. First, we have only demonstrated the technical feasibility of the proposed soft-hard composite pulse for fat suppression and water excitation in UTE imaging of both short and long T_2 tissues. No patients were studied in this work. Second, the proposed soft-hard pulse can only be used for nonselective 3D UTE imaging. A half-sinc pulse together with variable rate selective excitation may be used to replace the short rectangular pulse for slice/slab selective UTE imaging.[39] Third, the effect of the soft-hard composite pulse on quantitative UTE imaging remains to be investigated.

5 | CONCLUSION

The proposed soft-hard composite pulse is able to suppress fat signals while preserving both short and long T_2 signals, which is promising for both morphological and quantitative UTE imaging of short T_2 tissues.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

FIGURE S1 In vitro ankle UTE-Cones imaging (28-, 74-, and 84-year-old donors) using excitations with a single hard pulse (A-C), the proposed soft-hard water excitation pulse (D-F), and the conventional FatSat module (G-I). Fat was well suppressed by both the proposed soft-hard pulse and the FatSat module. The short T_2 tendon signal (indicated by yellow arrows in D-F) was much better preserved in the soft-hard excitation images (D-F) compared with FatSat images (G-I). The SSR color maps (soft-hard pulse: J-L; FatSat module: M-O) also suggest that there were almost no signal attenuations for either short or long T_2 tissues when using the proposed soft-hard pulse for excitation. In comparison, there were strong signal attenuations for the water signals in the FatSat UTE-Cones images, especially for the short T_2 tissues

TABLE S1 Mean and standard deviations of SSR values (%) of marrow fat, menisci, cartilage, quadriceps tendon, patellar tendon, ACL, PCL, cortical bone, Achilles tendon, and muscle in the knee, tibia, and ankle studies

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